

A PARAMETRIC STUDY ON USING ACTIVE DEBRIS REMOVAL FOR LEO ENVIRONMENT REMEDIATION

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Recent analyses on the instability of the orbital debris population in the low Earth orbit (LEO) region and the collision between Iridium 33 and Cosmos 2251 have reignited the interest in using active debris removal (ADR) to remediate the environment. There are; however, monumental technical, resource, operational, legal, and political challenges in making economically viable ADR a reality. Before a consensus on the need for ADR can be reached, a careful analysis of its effectiveness must be conducted. The goal is to demonstrate the need and feasibility of using ADR to better preserve the future environment and to guide its implementation to maximize the benefit-to-cost ratio. This paper describes a new sensitivity study on using ADR to stabilize the future LEO debris environment. The NASA long-term orbital debris evolutionary model, LEGEND, is used to quantify the effects of several key parameters, including target selection criteria/constraints and the starting epoch of ADR implementation. Additional analyses on potential ADR targets among the currently existing satellites and the benefits of collision avoidance maneuvers are also included.

I. INTRODUCTION

The 2009 collision between Iridium 33 and Cosmos 2251 highlighted the orbital debris problem – a side effect of more than 50 years of space activities. This problem was first recognized by Kessler and Cour-Palais (1978), and then by other researchers. The international space community collaborated to develop the commonly-adopted mitigation measures more than 15 years ago in hope of alleviating the problem. However, recent studies on the instability of the debris population in the low Earth orbit (LEO, defined as the region between 200 and 2,000 km altitudes) indicate that the environment has reached a point where collisions among existing debris will force the LEO population to increase, at least in the next 200 years, even without any new launches (Liou and Johnson, 2006, 2008). In reality, the situation will be worse than this “no future launches” scenario since satellite launches will continue and major breakups may continue to occur. Therefore, to better preserve the environment for future generations, active debris removal must be considered (Liou and Johnson, 2007, 2009a; Liou et al., 2010).

Active debris removal (ADR) means to remove objects from orbit above and beyond the currently-adopted mitigation measures. By this definition, lowering the orbit of a satellite at its end of life (EOL) to force the satellite to naturally decay within 25 years (“the 25-year rule”) or raising the orbit of a geosynchronous (GEO) satellite at its EOL to a graveyard orbit are not considered active debris removal. The idea of ADR is not new, but it has never been widely accepted as necessary or feasible,

primarily due to the tremendous technical challenges and cost involved. However, the recent instability studies and the collision between Iridium 33 and Cosmos 2251 have reignited the interests of using ADR to remediate the environment. In December 2009, the first International Conference on Orbital Debris Removal was hosted by NASA and DARPA in Washington, D.C., followed in April 2010 by the Debris Mitigation Workshop, organized by the International Science and Technology Center in Moscow, and then in June 2010, by the First European Workshop on Active Debris Removal, organized by CNES in Paris. The National Space Policy of the United States of America, released on 28 June 2010, also explicitly includes a guideline to “...mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment...” (Anon, 2010).

This paper’s intent is to extend the ADR simulations and analyses from previous studies further to explore different factors that might significantly affect the benefits of ADR. The focus of the study is on environment remediation modeling only. Issues such as cost, removal technology, ownership, legal and liability guidelines, and policy are outside the scope of the paper and will not be addressed. Section 1 provides a short review summary of the historical and current debris environment, including key information relevant to ADR. Section 2 contains the main part of the parametric study. It is organized, in logical order, into a “Top 10 list” format. Results from the parametric study are used to address the questions. Discussions and conclusions are summarized in Section 3.

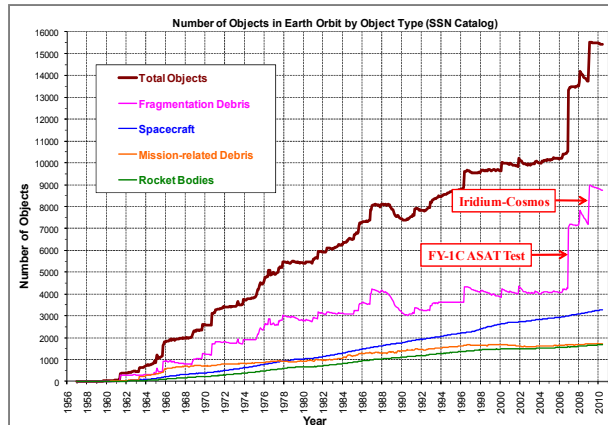


Fig. 1. The monthly increase of objects as cataloged by the U.S. Space Surveillance Network (SSN). The ASAT test and Iridium 33 / Cosmos 2251 collision fragments are responsible for the two recent major jumps.

II. GROWTH OF THE HISTORICAL DEBRIS POPULATION

Figure 1 illustrates the monthly increase of objects in Earth orbit as cataloged by the U.S. Space Surveillance Network (SSN). The top curve is the total and the population breakdown is represented by the four curves below it. Almost from the very beginning, the environment is dominated by fragmentation debris. The majority of the 203 known historical breakups between 1957 and 2010 were explosions. However, the two recent on-orbit collisions – the anti-satellite test on the Fengyun-1C (FY-1C) weather satellite conducted by China in 2007 and the collision between Iridium 33 and Cosmos 2251 in 2009, dramatically changed the landscape of the LEO environment. Fragments generated by these two events more than doubled

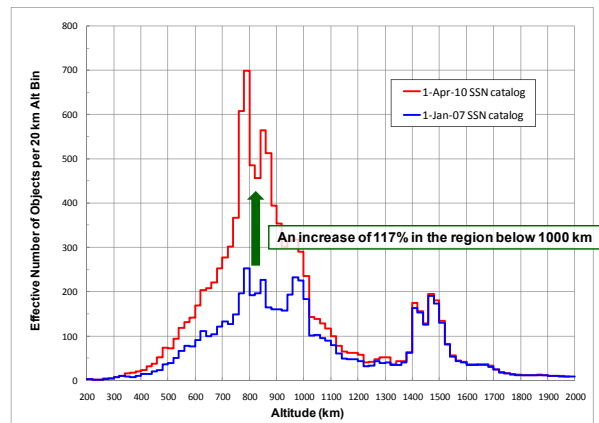


Fig. 2. Distributions of the SSN catalog objects in LEO at two different snapshots. The ASAT test and Iridium 33 / Cosmos 2251 collision fragments contribute to the majority of the difference between the two curves.

the environment below 1000 km altitude (Figure 2). The collision of Iridium 33 and Cosmos 2251, in particular, was a major milestone because it signaled a well-accepted trend that the future environment will be dominated by fragments generated via similar accidental collisions.

Currently, in terms of mass, there are about 5900 tons of materials in Earth orbit (not including the International Space Station), and more than 40% of the total (~2,500 tons) resides in LEO. As shown in Figure 3, there are three mass concentrations in LEO – around 600, 800, and 1,000 km altitudes. Rocket bodies (R/Bs) and spacecraft (S/Cs) represented about 97% of the mass in the region. The former dominates the 800 and 1,000 km peaks, whereas the latter dominates the 600 km peak. Figures 2 and 3 define the two key parameters controlling the collision activities in the environment. Additional discussions on the implication of these two parameters for ADR are described in the sections below.

III. THE TOP 10 LIST

The parametric study focused on objects 10 cm and larger because approximately 99% of the total mass in orbit comes from objects in this size regime. Numerical simulations were carried out using NASA's orbital debris evolutionary model, LEGEND (an LEO-to-GEO debris environment model). Descriptions of the model can be found in Liou et al. (2004) and Liou (2006). The future environment projection was limited to 200 years. It was somewhat subjective, but 200 years appeared to be a good balance between too short-sighted and too impractically long for this environmental study. The first half of the Top 10 list covers questions that have been addressed before (Liou and Johnson, 2009a; Liou et al., 2010). However, it is important to provide updated simulation results

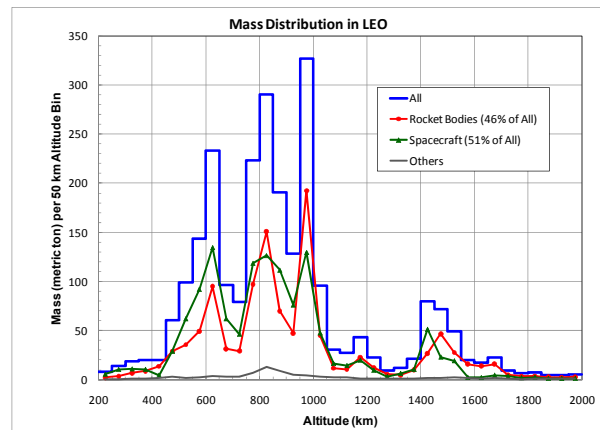


Fig. 3. Mass distribution in LEO. About 97% of the total mass is in rocket bodies or spacecraft. The ISS (~350 metric tons) is not included.

because the LEO environment was significantly altered after the ASAT test and the Iridium 33 / Cosmos 2251 collision. These updated results also paved the way for discussions on the remaining topics on the list.

3.1. Which region has the fastest projected growth rate and the highest collision activities?

The projected growth of the near-Earth debris environment, based on a “non-mitigation” (also known as the “business-as-usual”) scenario, is shown in Figure 4. The region between 35,586 and 35,986 km altitudes (i.e., within 200 km from the geosynchronous orbit) is defined as GEO. The region between LEO and GEO is defined as the medium Earth orbit (MEO). The three curves are averages from 100 Monte Carlo simulations. Error bars are the one sigma uncertainties of the averages. This scenario assumes no mitigation measures were applied to any current or future satellites. In essence, the projected growth of the debris populations under this assumption represents the worst-case scenario. It can be seen that the LEO population would follow a rapid non-linear increase in the next 200 years. This is a well-known trend that was the motivation for developing the currently-adopted international and various national mitigation measures more than 15 years ago. The projected growth in MEO and GEO, on the other hand, is very different from that in LEO. Even under this worst-case scenario, the growth is moderate. Only a few accidental collisions between ≥ 10 cm objects are predicted in MEO and GEO in the next 200 years. The currently-adopted mitigation measures, such as the end-of-life maneuvers in GEO, will further limit the population growth in these two regions. Therefore, by comparison, active debris removal is not a priority in MEO or GEO.

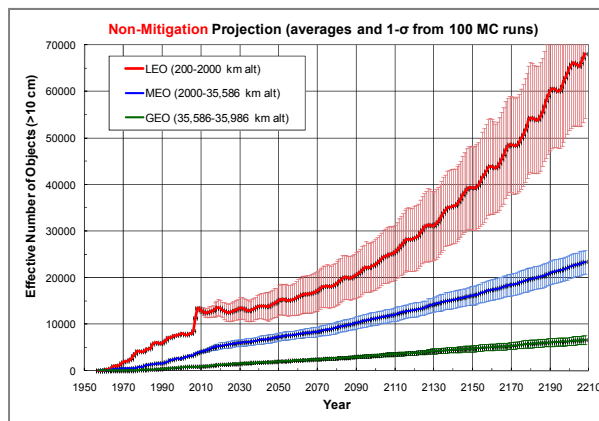


Fig. 4. Comparison of the cumulative collision probabilities of the benchmark and two ADR scenarios. Each curve is the average of 100 LEGEND Monte Carlo runs.

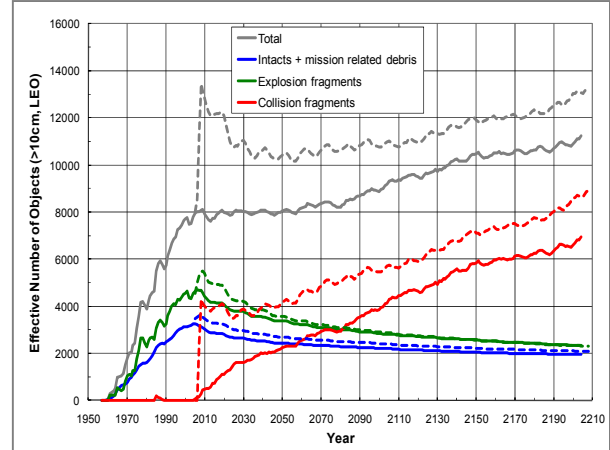


Fig. 5. Comparison of the spatial density distributions for objects 10 cm and larger. The dashed curve is the environment at the beginning of the future projection.

3.2. Can the commonly-adopted mitigation measures stabilize the future LEO environment?

The study by Liou and Johnson (2006) indicated that the LEO debris population had reached a point where the environment was unstable and mutual collision would force the population to increase even without any future launches. Figure 5 shows the result of an updated simulation where the historical environment was extended through the end of 2009, followed by a 200-year future projection under the same “no future launches” assumption. The major difference between Figure 5 and the 2006 result was the inclusion of fragments generated from the FY-1C breakup and the collision between Iridium 33 and Cosmos 2251. The total population reflects the balance between source and sink. The former includes fragments generated by new breakups while the latter includes the natural decay of objects. Overall, the net impact of the FY-1C breakup and the collision between Iridium 33 and Cosmos 2251 is an increase of about 2500 objects (including fragments generated from collisions induced by fragments from these two events) for the next 200 years. The short-term decrease in the total population before 2030 is caused by the rapid decay of high area-to-mass ratio objects, such as multi-layer insulation, solar panel, or lightweight composite debris in the FY-1C and Iridium fragment clouds (Liou and Johnson 2009b; Liou 2009).

The total populations from the two simulations (the top two curves in Figure 5) follow a similar trend, i.e., even without any future launches the population will not decrease. Rather, fragments generated from mutual collisions among existing objects will force the population to increase over time. In reality, the

situation will be worse than the “no future launches” scenario because satellite launches will continue and unexpected major breakups may continue to occur. Postmission disposal, such as the 25-year decay rule, will help, but will be insufficient to prevent the debris self-generating phenomenon from happening. To preserve the near-Earth space for future generations, ADR must be considered.

3.3. What are the objectives of ADR?

The development of ADR technologies and the execution of ADR are driven by top-level mission objectives. A well-thought-out strategy and a balanced, long-term roadmap are needed to ensure the best outcome for the environment. Common mission objectives include maximizing the benefit-to-cost ratio and following practical/operational constraints in altitude, inclination, class, or size-of-the-target objects. Specific objectives include, for example, controlling the population growth (≥ 10 cm or others), limiting collision activities, mitigating short- or long-term risks (damage, not necessarily catastrophic destruction) to selected payloads, mitigating risks to human space activities, and so on.

If, for example, the objective is to reduce the impact risks to the U.S. modules of the International Space Station (ISS), then the objects to be targeted for removal must first be identified. The U.S. modules on the ISS are equipped with impact shields strong enough to withstand impacts from orbital debris smaller than 1.35 cm in size (Hyde et al., 2010). Currently the number of objects larger than 1.4 cm with orbits crossing that of the ISS is about 1200. Since the debris population follows a power-law size distribution, the great majority of the 1200 objects, about 800 of them, are between 1.5 and 3 cm. Therefore, to reduce 50% of the ISS-crossing orbital debris in this size range (1.5 cm to 3 cm) will require the technology and the deployment of a debris remover/collector with an area-time product on the order of 1000 km² year.

3.4. How can effective ADR target selection criteria to stabilize the future LEO environment be defined?

The future debris environment is likely to be dominated by accidental collision fragments. This phenomenon is popularly known as the “Kessler Syndrome” after the pioneer work by Kessler and Cour-Palais (1978). If the ADR objective is to reduce the population growth, then the effort should focus on limiting accidental collision fragments. In other words, the best ADR strategy to meet this mission objective is to target objects with the highest collision probabilities and objects with the potential of generating the greatest amount of fragments upon collision. Based on this

simple physical argument, an effective ADR target selection criterion, R_i , can be defined as:

$$R_i(t) = P_i(t) \times m_i,$$

where m_i is the mass of any object i , and $P_i(t)$ is its collision probability at time t (Liou and Johnson, 2007, 2009a). In addition to this selection criterion, GTO objects should not be considered for removal because they only spend a small fraction of time below 2000 km and consequently, have negligible contributions to the LEO collision activities. Breakup fragments should be excluded as well because their overall mass is small compared with those of rocket bodies and spacecraft (see Figure 3). The uncertainty in estimating the mass of individual fragments also makes it difficult to apply a mass-dependent selection criterion. Various numerical simulations have been conducted to validate the benefits of using these selection criteria for efficient control of the future population growth in LEO (Liou and Johnson, 2007, 2010).

3.5. What are the keys to remediate the future LEO environment?

Figure 6 summarizes the results of an updated ADR simulation where fragments from the FY-1C breakup and the collision between Iridium 33 and Cosmos 2251 were included in the historical environment. All three test cases assumed future launches could be represented by the traffic cycle from the last 8 years and the commonly-adopted post-mission disposal (PMD) measures, including the 25-year rule, were applied to R/Bs and S/Cs with a 90% success rate. The two ADR scenarios further assumed a routine ADR was implemented, starting from the year

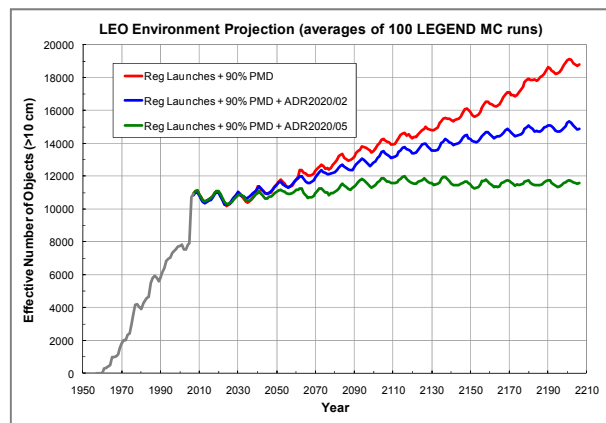


Fig. 6. LEO population growth as a function of time. To maintain the future LEO population at the current level requires a good implementation of the mitigation measures and an ADR removal rate of five objects per year starting from the year 2020.

2020, and criteria described in Section 3.4 were used to prioritize objects for removal. The comparison clearly shows that to maintain the LEO population at a level comparable to the current environment requires (1) a 90% successful implementation of the commonly-adopted mitigation measures and (2) a removal rate of five objects per year. This scenario, demoted as “Reg Launches + 90% PMD + ADR2020/05” in the figure, is referred to as the “benchmark scenario” and is used for additional comparisons with other test cases in the following sections.

The “mass in orbit” and “mass removed” distributions from the three test cases are shown in Figure 7. Under the 90% PMD scenario, the mass in LEO is actually kept at a constant level. However, this level apparently is above the threshold of instability. The removal rate of five objects per year, based on the target selection criteria outlined in Section 3.4, requires an average of 6.8 tons of mass being removed from orbit every year.

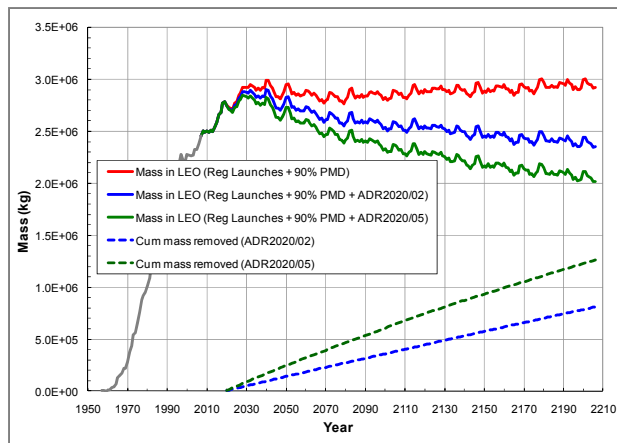


Fig.7. The top three curves depict the masses in LEO from the three different scenarios. Each LEO-crossing object’s mass is weighted by its time residing between 200 and 2000 km altitudes. The bottom two curves show the cumulative masses removed from the two ADR scenarios.

3.6. What is the best timeframe for ADR implementation?

From the projected increase of the future LEO debris population, a common-sense approach would argue for a timely implementation of ADR for environment remediation. However, the expectation that ADR can be carried out as a routine task as early as 2020, such as the assumption made in the simulations described above, may be too optimistic. A simple comparison was made to quantify the effects of a later implementation of ADR. The results are summarized in Figure 8. The middle curve is the

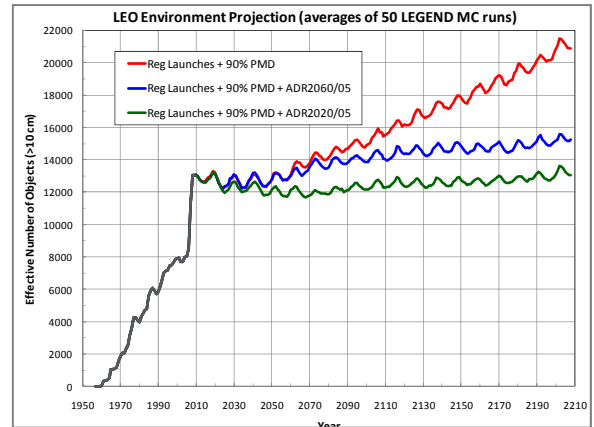


Fig. 8. The projected growths of the future LEO debris population from three test scenarios. ADR2020/05 means active debris removal starts with the year 2020 and the removal rate is five objects per year. ADR2060/05 means active debris removal starts with the year 2060 and the removal rate is five objects per year.

projected population growth based on an ADR rate of five objects per year, starting from the year 2060. The average numbers of collisions predicted by the three scenarios (top to bottom curves), are 47, 32, and 25, respectively. Moving ADR implementation from 2020 to 2060 would lead to 7 more collisions and about 2000 more objects in the environment for the next 200 years. How significant these differences are and whether or not they are acceptable depend on many factors. To reach a consensus on a reasonable ADR implementation timeline will require detailed trade-off studies to balance the negative impacts to the environment (including risks to operational satellites) and the time needed to develop cost-effective ADR technologies.

3.7. What is the effect of practical/operational constraints?

In addition to the criterion of Eq. (1), the nature of removal operations is likely to favor the selection of removal targets in limited altitude, inclination, right ascension of the ascending node, or size regimes. Vehicle type/class may need to be considered as well. These additional but necessary constraints will have some impact on the effectiveness of an ADR strategy solely based on Eq. (1). Figure 9 shows the altitude versus inclination distributions of the currently existing R/Bs and S/Cs with masses above 50 kg. Crosses and open circles represent the apogee and perigee altitudes, respectively. The majority of the R/Bs and S/Cs are concentrated in about 10 narrow inclination bands over 3 altitude regions (see also Figure 3). To analyze the effect of additional selection constraints, a special

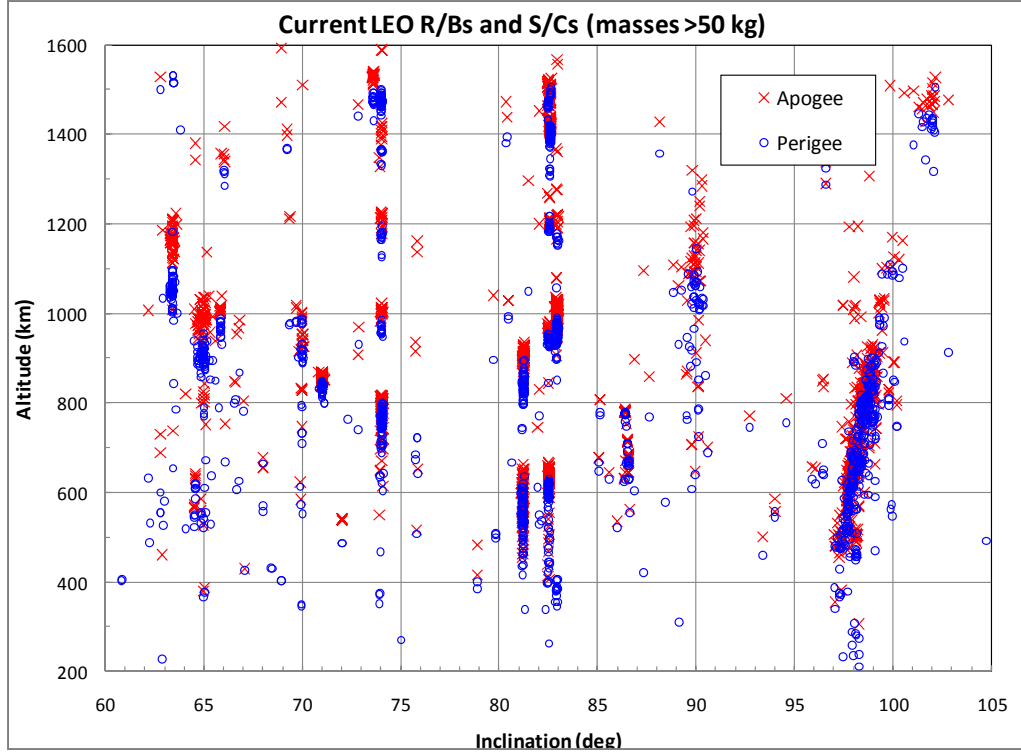


Fig. 9. Apogee altitude (crosses) and perigee altitude (open circles) versus inclination distributions of the current LEO R/Bs and S/Cs. Only those with masses above 50 kg are shown. Additional selection constraints in inclination (82.5° to 83.5°) and altitude (900 to 1050 km) are applied to ADR targets for the special comparison.

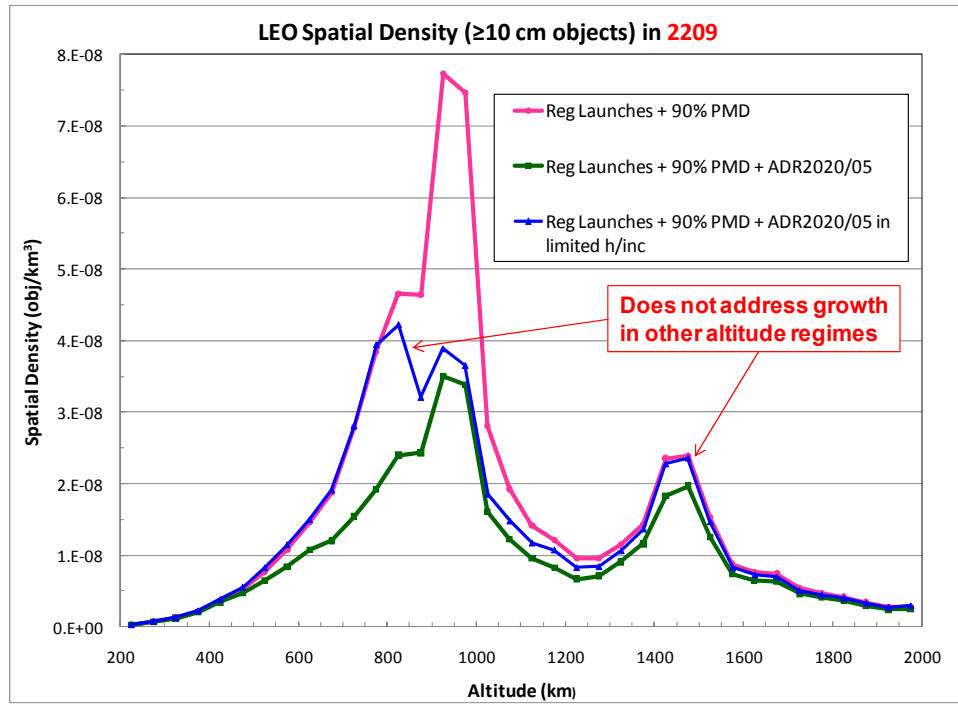


Fig. 10. Object spatial density distributions at the end of the 200-year future environment projection. The middle curve shows the results from the special LEGEND run where additional constraints are applied to targets selected for removal.

LEGEND simulation was performed where ADR targets were limited to objects with the highest mass, with collision probability products between 82.5° and 83.5° and located between 900 and 1050 km altitudes. The spatial density distributions at the end of a 200-year future projection from three scenarios are compared in Figure 10. As expected, limiting ADR targets to a specific altitude will not address the

population growth in other regions, such as 800 km or 1450 km. In addition, limiting ADR targets to a narrow inclination band may not be the most efficient way to control the population growth in the same altitude region. This is because vehicles in the same altitude region, but with different inclinations, may also contribute significantly to collision activities in the environment.

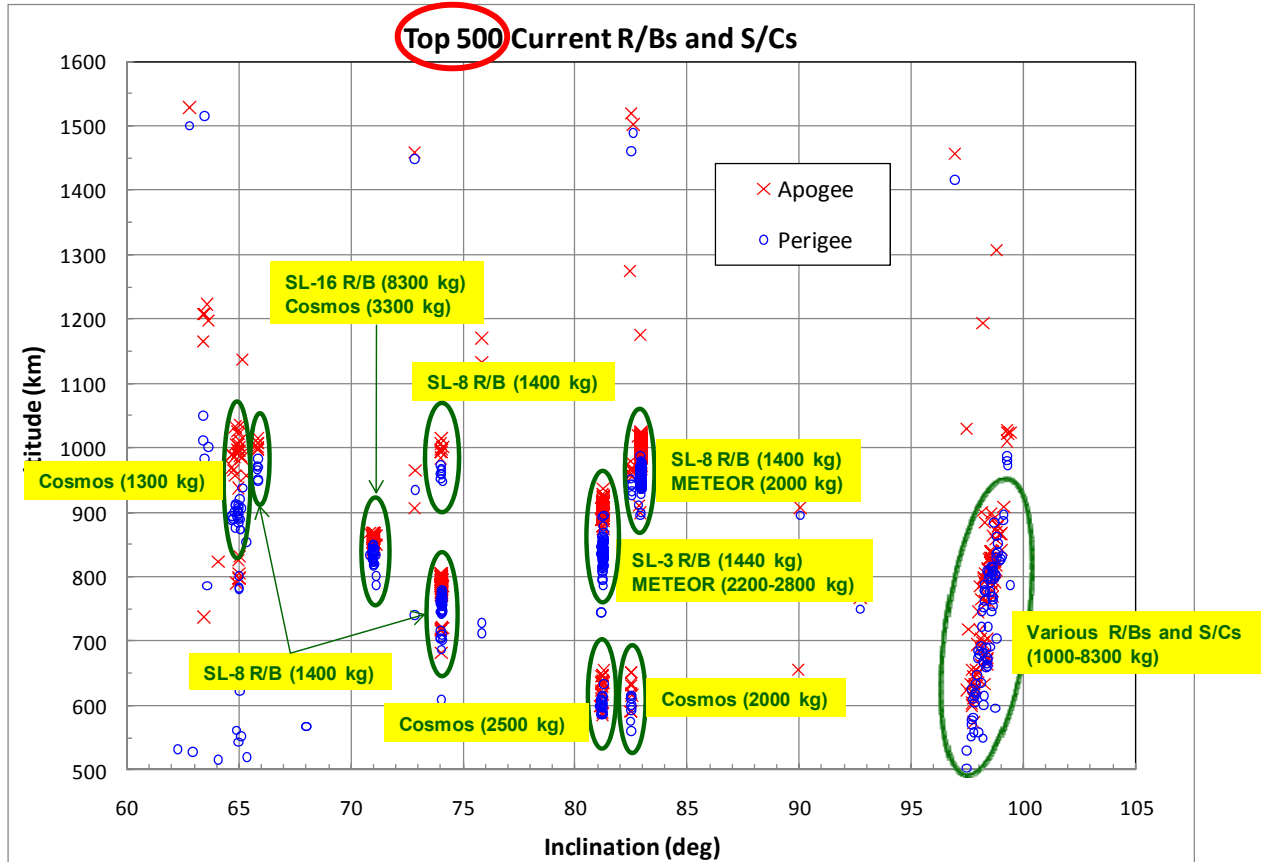


Fig. 11. Apogee altitude (crosses) and perigee altitude (open circles) versus inclination distributions of the existing LEO R/Bs and S/Cs that have the highest mass and collision probability products. Only the top 500 are shown.

3.8. What are the collision probabilities and masses of objects in the current environment?

Of all the R/Bs and S/Cs in the current environment, those with the highest (top 500) mass and collision probability products are shown in Figure 11. The prograde region is dominated by several well-known classes of vehicles: SL-3 R/Bs (1440 kg dry mass), SL-8 R/Bs (1400 kg dry mass), SL-16 R/Bs (8300 kg dry mass), and various meteor-series and cosmos S/Cs (masses ranging from 1300 to 2800 kg). Below 1100 km altitude, the numbers of SL-3, SL-8, and SL-16 R/Bs with nearly circular orbits are 39, 211, and 18, respectively. The total masses for SL-3, SL-8, and SL-16 R/Bs in this region are approximately 56, 295, and 149 tons, respectively. Objects in the

retrograde region are more diverse. They include, for example, Ariane R/Bs (1700 kg dry mass), CZ-series R/Bs (1700 to 3400 kg dry mass), H-2 R/Bs (3000 kg dry mass), SL-16 R/Bs, and S/Cs such as Envisat (8000 kg) and meteorological satellites from various countries. The total mass in the retrograde region is about 220 tons with approximately equal contributions from R/Bs and S/Cs. If ADR were to be implemented in the near future, objects in Figure 11 should have the highest priorities. New ground-based observations on those objects, especially the R/Bs, need to be conducted first to identify their tumbling states. The data can guide the development of the capture mechanism for ADR techniques that require proximity operations with the target objects.

3.9. What are the benefits of collision avoidance maneuvers?

Since the collision between Iridium 33 and Cosmos 2251, the U.S. Department of Defense's Joint Space Operations Center has been conducting conjunction assessments for all active S/Cs and providing the information to the operators or owners of the S/Cs involved. Approximately 80% of the active S/Cs in LEO have maneuvering capability. Collision avoidance (COLA) maneuvers can certainly prevent S/Cs from colliding with objects in the catalog and reduce the generation of collision fragments in the future. The benefits of COLA in reducing the LEO population growth is analyzed below.

The first step to quantify the benefits of COLA is to identify active S/Cs with maneuvering capabilities. Since it is very difficult to develop a complete list, a good way to envelop the problem is to assume all S/Cs with lifetimes less than 9 years are active and all have COLA capability. Based on this assumption, the mass distribution of the identified 2010 active S/Cs is compared with the mass distribution in LEO in Figure 12. The total mass of the "active" S/Cs only accounts for about 9% of the mass in the environment. This comparison shows that "active" S/Cs do not represent a major source of mass in LEO. A more quantitative comparison is shown in Figure 13. As illustrated, a LEGEND simulation where all "active" S/Cs (those less than 9 years old at any point in time) were excluded from collision consideration in future projection was conducted. The result was compared with the benchmark case. The difference between the two curves is not very significant.

One footnote on COLA – it does not protect S/Cs from non-catalog objects. The impact damage to a payload or its critical components depends on the

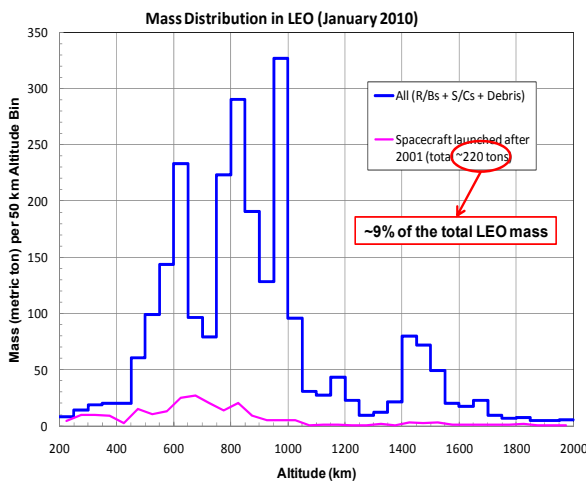


Fig. 12. Mass distribution of all objects in LEO (histogram) and the mass distribution of "active" S/C (bottom curve).

size of the impacting particle. Objects smaller than 10 cm can still cause serious damage or be lethal to the vehicle. Therefore, the LEO population growth is a concern to every satellite operator/owner.

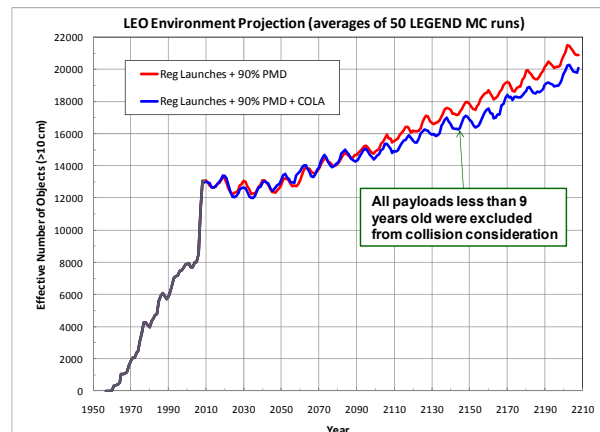


Fig. 13. The projected growths of the future LEO debris population from two test scenarios. The top curve is the benchmark scenario. The bottom curve represent a special LEGEND simulation where "active" S/Cs were excluded from collision consideration in the future projection.

3.10. What are the challenges ahead?

Orbital debris is a problem for all space-faring nations. The international community must first reach a consensus on the instability problem of the LEO debris environment. The next step is to determine if there is a need to use ADR for environment remediation. Just because the population will increase by 60% in the next 200 years does not mean ADR is imminent. The cost of losing and replacing one operational satellite every 10 years may be affordable. In other words, the international community must agree on what degree of loss is acceptable. Once a decision to move forward is made, then detailed trade-off studies must be conducted to establish a reasonable timeframe for the ADR implementation. During the process, the involved parties have to commit necessary resources to support the development of low-cost and viable removal technologies and the execution of the actual removal.

IV. CONCLUDING REMARKS

This paper provides an update on the status of the orbital debris environment and shows, quantitatively, why there is a need to consider ADR for environment remediation. Key questions are presented and LEGEND simulations are used to illustrate and support various arguments. The goals of the study are to highlight the complexity of debris removal and to demonstrate the type of analyses that would be needed to gain a better picture of the difficulties involved. In

addition to the technical challenges, it is well-understood that issues such as policy, cost, coordination, ownership, and legal and liability guidelines also need to be addressed at the national and international levels if ADR is to be implemented to better preserve the environment for the future generations.

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